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Dynamic pressure measurement of cartridge operated vole captive bolt devices

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ABSTRACT

Introduction: Vole captive bolt devices are powder actuated spring guns that are used as a pest control mean. After having triggered the explosion of the blank cartridge by touching a metal ring around the muzzle, the vole is killed by the massive propulsion of the gas jet. Improper use and recklessness while handling these devices may cause severe injuries with the hand of the operator at particular risk. Currently, there are no experimental investigations on the ballistic background of these devices.
Methods: An experimental test set-up was designed for measurement of the firing pressure and the dynamic force of the gas jet of a vole captive bolt device. Therefore, a vole captive bolt device was prepared with a pressure take-off channel and a piezoelectric transducer for measurement of the firing pressure. For measurement of the dynamic impact force of the gas jet an annular quartz force sensor was installed on a test bench. Each three simultaneous measurements of the cartridges' firing pressure and the dynamic force of the blast wave were taken at various distances between muzzle and load washer.
Results: The maximum gas pressure in the explosion chamber was up to 1100 bar. The shot development over time showed a typical gas pressure curve. Flow velocity of the gas jet was up to 2000 m/s. The maximum impact force of the gas jet at the target showed a strong inverse ratio to the muzzle's distance and was up to 11,500 N for the contact shot distance. Energy density of the gas jet for the close contact shot was far beyond the energy density required for skin penetration.
Conclusion: The unique design features (short tube between cartridge mouth and muzzle and narrow diameter of the muzzle) of these gadgets are responsible for the high firing pressure, velocity and force of the gas jet. These findings explain the trauma mechanics of the extensive tissue damage observed in accidental shots of these devices.

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1. Introduction

Vole captive bolt devices are powder actuated stationary spring guns that are widely used as a pest control mean. They are operated with cal. 9×17 central fire industrial blank cartridges. These traps are embedded into the vole passage, the vole is killed by a high pressure gas jet after having triggered the explosion of the cartridge. Improper use and recklessness while handling these devices may cause severe injuries with the hand of the operator at particular risk [1]. A contact shot from this extremely short barrelled gun may cause typical findings combining a large stellate entrance wound and a powder cavity with extensive undermining of the soft-tissue and destruction of the adjacent anatomical structures. The lesions combine a variety of tissue destruction (laceration, dissemination, avulsion, blast, crush and burns) [2]. Outcome of these injuries is poor, deterioration of hand function is almost inevitable [3].

Vole captive bolt devices operate by means of explosive substance, therefore they have to bear an official proof-test mark. Currently, there are two different models of vole captive bolt devices approved and available (model Auber, Germany and Kieferle, Germany). They are similar in design. With regard to ballistic considerations, the relevant parts of the devices are identical. Both gadgets are featured with a screwable explosion chamber. The dimensions of the muzzles (diameter 4 mm) and the cartridge chambers are identical (volume 1.4 cm^3) (Fig. 1). Both models are operated with cal. 9×17 industrial cartridges (maximum energy value 700 J) [4].

Industrial cartridges are intended as explosive substance in powder-actuated tools. They are widely used in portable devices, industrial or professional tools to propel either a projectile (nail-guns) or some other mechanical component part (captive bolt stunners).

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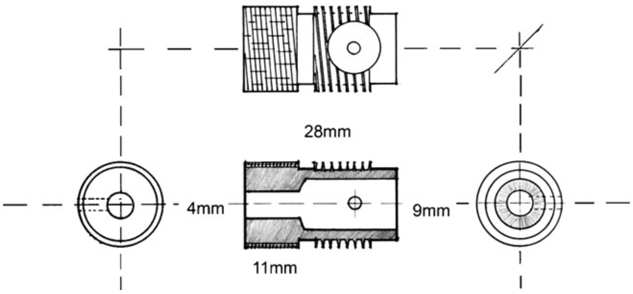

Fig. 1. Engineering drawing of the cartridge chamber of vole captive bolt devices with the pressure take off bore hole. Ballistic relevant characteristics are defined by the volume of the chamber (1.4 cm^3) and the small diameter of the muzzle (4 mm) which is necked down from the 9 mm cartridge chamber. A short tube of only 11 mm is interposed between cartridge mouth and muzzle. The upper drawing indicates the measuring point of the piezoelectric transducer.

Industrial blank cartridges contain nitrocellulose as single base propellant. They release their energy by deflagration, a process of rapid chemical burning. Flame temperature of nitrocellulose runs about 2500–3000 °C (4530–5430 °F) [5]. The space formerly occupied by the explosive is filled with gas under high pressure and temperature. This results in a pressure gradient at the muzzle.

The gas jet of these shooting devices can be considered as a mass flow with a certain flow velocity. The impact at the target is defined both by the mass and the velocity of the mass flow and the time duration of the contact. At high velocity this mass flow bears considerable kinetic energy and can be compared with a projectile [5–7].

Currently, there are no investigations of the ballistic background of these vole captive bolt devices nor are there any investigations of the propellant expansion of the industrial blank cartridges intended as ammunition.

1.1. Aim of this investigation

It is the aim of this work to describe for the first time an experimental set up for measurement of both firing pressure and dynamic force of the gas jet of cartridge operated vole captive bolt devices and to determine these parameters.

2. Materials and methods

2.1. Test set up for measurement of the firing pressure and the dynamic force of the gas jet

A vole captive bolt device (model Auber, Germany, bearing the type approval sign PTB 2) was prepared for measurement of firing pressure by drilling a 10 mm thread (M10 × 1) as pressure take off channel into the casing. A borehole (2.5 mm in diameter) was drilled into the thread of the screwable explosion chamber, concentric in relation to the pressure take off channel. A piezoelectric transducer (Type 6215, Kistler Instrumente AG, Winterthur, Switzerland) was screwed into the measuring hole of the casing for firing pressure measurement (Fig. 2).

Commercial industrial blank cartridges (RWS Dynamit Nobel, Fürth, Germany, calibre 9 × 17, yellow mark, maximum energy value 700 J) which contain a 390 mg nitrocellulose charge and are legally assigned for the use in vole captive bolt devices were pierced concentrically (diameter of the drill hole 2 mm) to line up with the hole for taking pressure in the pressure take off channel. Obturation of the hole drilled in the case of the cartridges was achieved by means of a heat resistant adhesive tape (Tesa 4118 PVI) (Fig. 3).

For measurement of the dynamic impact force ("Punch Force") of the blast wave a test bench was constructed. An annular Quartz force sensor (load washer, 1-component force sensor, Type 9051, Kistler Instrumente AG, Winterthur, Switzerland) was installed between two plane-parallel, rigid and fine-machined faces (diameter of the sensor surface 39.8 mm) opposite to the muzzle of the vole captive bolt device which was fixed on a continuously adjustable test bench to vary the distance between the muzzle and the annular membrane transducer (Fig. 4). To avoid local overloads and damage to the sensor surfaces a force distributing ring was used.

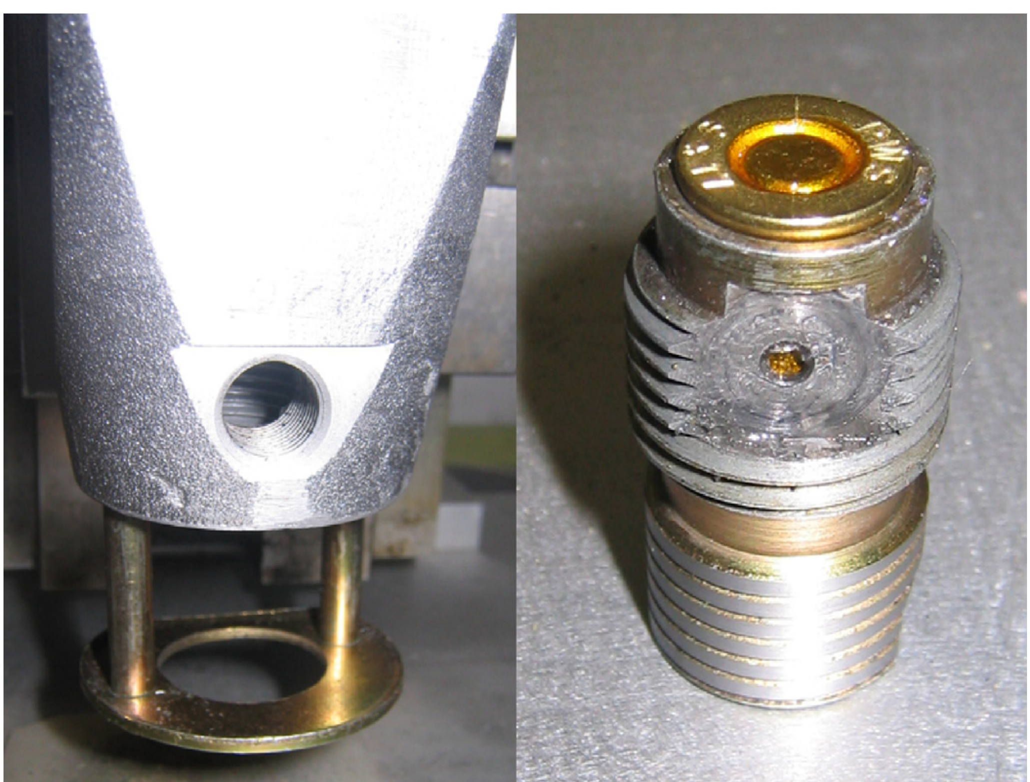

Fig. 2. Vole captive bolt device prepared with a 10 mm measuring channel to take in the piezoelectric transducer (left), screwable explosion chamber prepared with a 2.5 mm borehole for pressure take-off (right). The chamber is loaded with a concentrically pierced 9 × 17 industrial blank cartridge (Fig. 3), the hole drilled in the case of the blank cartridge is concentric and coaxial with the channel ducting the pressure from the exploding cartridge.

Fig. 3. Industrial blank cartridges that are legally assigned for operating vole captive bolt devices. The cases of the cartridges were pierced concentrically (2 mm drill hole) with the bore hole in the screwable explosion chamber and with the pressure take-off channel of the vole captive bolt device. Obturation of the hole was achieved by means of a heat resistant adhesive tape.

The measurement chain was completed by two charge amplifiers to convert the signals provided by the piezoelectrical transducers into a voltage (Type 5015A, Kistler Instrumente AG, Winterthur, Switzerland).

Each three simultaneous measurements of the cartridges' firing pressure and the dynamic force of the blast wave were taken at various distances between muzzle and load washer (250 mm, 150 mm, 100 mm, 50 mm, 25 mm and 3 mm). The 3 mm distance is the trigger-distance of a close contact shot.

2.2. Data analysis and processing

Dynamic measurements of the gas pressure and the dynamic force of the gas jet over time were analysed. The flow velocity of the gas jet was calculated from the time lag between peak value of the gas pressure ($t_{P_{max}}$) and peak value of the dynamic force ($t_{F_{max}}$). The total impulse was determined by the integral of the force–time–graph. The area under the curve was bounded by the time reaching the threshold value of 170 N. This threshold value was determined dependent on the sensor surface according to the 1.5 bar threshold used by Kneubuehl [6]. To determine the wounding potential the energy density of the gas jet was calculated using impulse, velocity of the gas jet and sensor surface of the load washer.

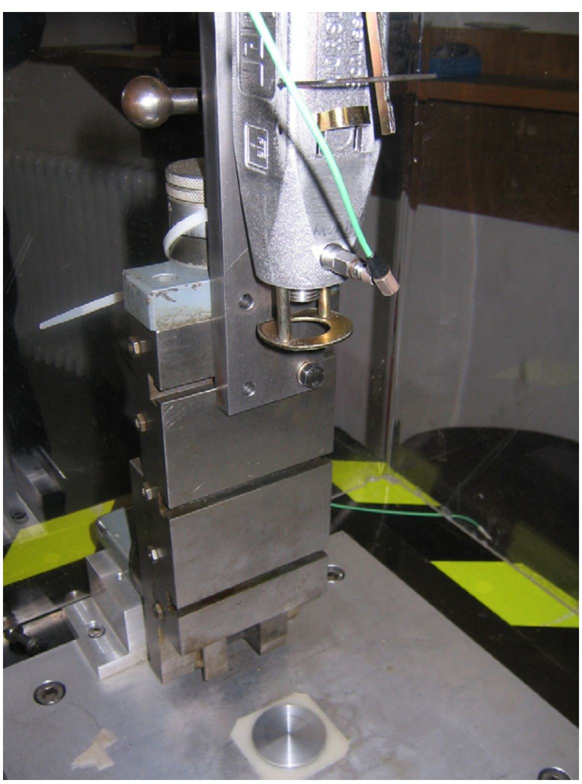

Fig. 4. Test set up for simultaneous measurement of the cartridge's firing pressure and the dynamic force of the gas jet. A piezoelectric transducer is screwed into the casing of the shooting device. The distance between muzzle and target (annular transducer at bottom) can be varied between 250 mm and 3 mm.

All measurements were taken in a completely enclosed shooting test stand free from weather influences. Multi channel data acquisition and analysis were performed using Trans PC and TransAS v.2.6.5 (Elsys AG, Niederrohrdorf, Switzerland). Graph analysis was performed using Origin (Originlab Corp., Northampton, MA), statistical analysis was performed using SPSS 16.0.1 (SPSS Inc., Chicago, IL).

3. Results

3.1. Internal ballistics, measurement of the firing pressure

The average maximum gas pressure (average P_{max}) was 927.9 bar (range, 813.6–1098.3 bar, S.D. 87.1 bar) (927.9×10^5 Pa, range 813.6×10^5–1098.3×10^5 Pa, S.D. 87.1×10^5 Pa).

The shot development over time of the industrial blank cartridges in the explosion chamber shows a typical gas pressure–time curve (Fig. 5). The sequence is divided into different phases, time 0 is where the striking pin hits the ignition cap. The ignition phase reaches from 0 to $t_{10\%}$, where $t_{10\%}$ is defined at the time to reach 10% of the maximum gas pressure. Ten percent of the maximum gas pressure were reached after 106.8×10^{-6} s on average (range, 82.8×10^{-6}–123.7×10^{-6} s, S.D. 14.5×10^{-6} s). The propellant transformation phase (PTP) starts when 10% of the maximum gas pressure are reached and ends with the falling gas pressure curve once the powder has been fully transformed ($t_{P_{max}}$). The propellant transformation phase, which is a parameter determining the burn rate of the cartridge, was 148.5×10^{-6} s on average (range, 115.2×10^{-6}–177.5×10^{-6} s, S.D. 18.7×10^{-6} s).

3.2. External and terminal ballistics of the gas jet

The flow velocity of the gas jet was calculated from the time lag between peak value of the gas pressure ($t_{P_{max}}$) and peak value of the dynamic force ($t_{F_{max}}$). With increasing distance to the muzzle a decreasing flow velocity was found. Average velocity was highest for the 0.3 cm distance (1966.2 m/s, range 1621.6–2276.9 m/s), and lowest for the 25 cm distance (470.9 m/s, range 446.7–490.14 m/s).

The maximum impact force of the gas jet at the target showed a strong inverse ratio to the muzzle's distance and was highest for the 0.3 cm distance (11134.5 N, range 10588.3–11451.0 N) and lowest for the 25 cm distance (425.2 N, range 378.8–450.0 N).

To assess the ballistic effectiveness of these shooting traps, the total impulse and the energy density of the gas jet was determined. Both parameters were highest for the shortest distance to the muzzle and follow an exponential decrease. For the 0.3 cm close contact shoot, total impulse was 0.782 N s on average (range, 0.704–0.841 N s) while energy density was 0.624 J/mm^2 (range, 0.459–0.770 J/mm^2). Even at the 2.5 cm distance total impulse was 0.324 N s (range, 0.297–0.345 N s) and the energy density was

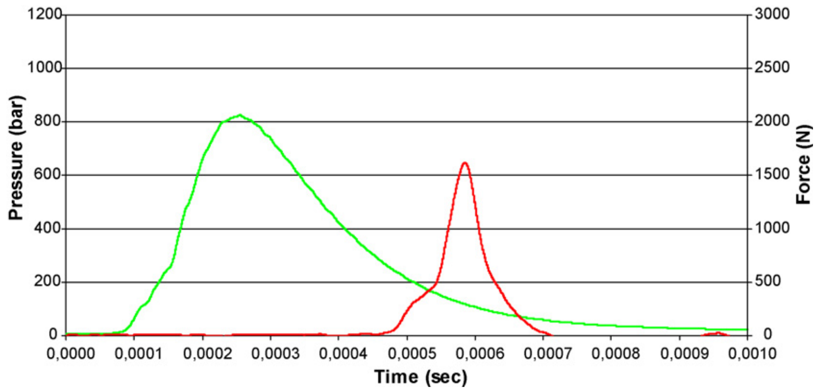

Fig. 5. Gas pressure curve (green graph) and dynamic force of the gas jet at the target (red graph), distance between muzzle and target transducer 15 cm. P_{max} 825.1 bar, F_{max} 1615.8 N. Velocity of the gas jet is calculated by the time lag between $t(P_{max})$ and $t(F_{max})$. Total impulse is graphically determined as the integral under the red force–time–graph, the area under curve is bounded by the time reaching the threshold value of 170 N.

0.127 J/mm^2 (range, 0.125–0.130 J/mm^2) which is still higher than the energy density required for skin penetration (0.1 J/mm^2).

For details on the data see Table 1. Development of maximum gas pressure, maximum impact force, jet velocity, impulse and energy density as a function of muzzle-target-distance are shown in Figs. 6 and 7.

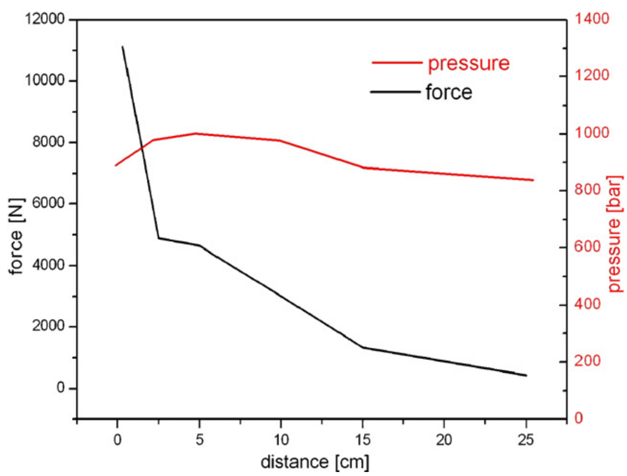

Fig. 6. Development of maximum gas pressure (red graph) and maximum impact force (black graph) as a function of muzzle-target-distance.

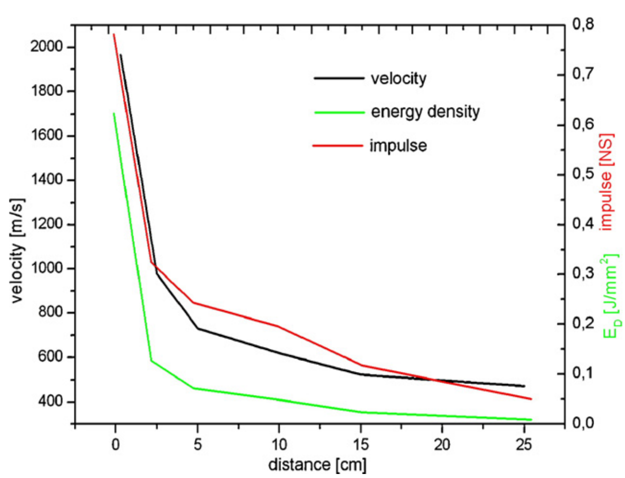

Fig. 7. Development of jet velocity (black graph), impulse (red graph) and energy density (green graph) as a function of muzzle-target-distance.

4. Discussion

As other powder actuated tools, vole captive bolt devices bear a certain potential for injury. Carelessness, improper use and foolish behaviour have been identified as major risk factors [1]. Though no projectile is used, various substances are discharged from the muzzle in addition to the gas jet (metallic fragments of the cartridge, waxen shutter cap of the cartridge, burning grains of powder, and a metallic spray of primer).

Although precursors of the current vole captive bolt devices have been developed more than 70 years ago and the current cartridge operated traps are widely used for pest control means since more than 40 years, the mechanism of propellant expansion and the underlying trauma mechanics of these unique gadgets has not been investigated yet.

For blank-firing hand guns, it has been repeatedly demonstrated that the gas jet may possess a relevant potential for injury [8–19]. Rothschild and Kneubuehl investigated the gas pressure of blank cartridges (calibres 8 mm, .380, 9 mm PA) at the cartridge mouth and at the muzzle of a test barrel. Maximum gas pressure measured was 48–184 bar at the cartridge mouth and 1.0–1.6 bar at the muzzle [6,20]. As there is a great pressure gradient at the muzzle of a shooting device, pressure measurement at this point is very unreliable and susceptible to faults. Therefore, in our test set up the dynamic force at the target rather than the free-field pressure was chosen to quantify the impact of the gas jet.

As previous investigations on ballistics of guns have demonstrated, gas pressure and velocity of the gas jet at the muzzle increases with shortening of the barrel [15,21].

With regard to the potency for wounding, Kneubuehl divides blank firing weapons into two categories: short barrelled guns (energy density of 0.45–0.75 J/mm^2) and weapons bearing a long barrel (barrel length >120 mm for pistols and >135 mm for revolvers) with an energy density of 0.25 J/mm^2 [6]. The average energy density of 0.624 J/mm^2 even in 0.3 cm distance to the muzzle of a vole captive bolt device is higher than the energy density measurements reported for almost any blank-firing hand gun at this distance and higher than the energy densities required for causing penetrating wounds at any anatomical region [6,22]. Therefore, a close contact shot of a vole captive bolt device to the body surface will cause penetrating wounds and might even penetrate the body cavities. The unique design features of vole captive bolt devices (e.g. the short 11 mm tube between mouth of the cartridge and muzzle and the small diameter of the muzzle of only 4 mm) and the unique characteristics of the cal. 9 × 17 industrial blank cartridges (higher powder charge compared with common blank cartridges) give the reason for the higher ballistic

Table 1
Internal, external and terminal ballistic parameters. Each three shots per distance were averaged, ranges are given below the average values.

Distance, d (cm)	Gas pressure (cartridge chamber)			PTP[a], Δt ($\times 10^{-6}$ s)	Velocity, v (m/s)	Dynamic force		Impulse, p (NS)	Energy density, ED (J/mm^2)
	P (bar)	P (Pa)	P (psi)			F (N)	F (lbf)		
0.3	889.3	889.3×10^5	12898.2	149.7	1966.2	11134.5	2503.1	0.782	0.624
	856.0–937.9	856.0×10^5–937.9×10^5	12415.3–13603.1	137.1–166.4	1621.6–2276.9	10588.3–11451.6	2380.3–2574.4	0.704–0.841	0.459–0.770
2.5	979.2	979.2×10^5	14202.1	147.1	979.6	4890.3	1099.4	0.324	0.127
	854.3–1098.3	854.3×10^5–1098.3×10^5	12390.6–15929.5	115.2–169.1	898.2–1059.9	4633.2–5076.2	1041.6–1141.2	0.297–0.345	0.125–0.130
5.0	1002.5	1002.5×10^5	14540.1	134.5	730.6	4641.1	1043.4	0.243	0.072
	960.3–1083.0	960.3×10^5–1083.0×10^5	13928.0–15707.6	123.2–141.6	718.2–754.4	4034.4–4970.3	907.0–1117.4	0.192–0.330	0.055–0.099
10.0	977.8	977.8×10^5	14181.8	144.6	618.3	3006.1	675.8	0.196	0.049
	928.1–1007.0	928.1×10^5–1007.0×10^5	13461.0–14605.3	130.5–153.2	577.1–669.8	2645.5–3241.6	594.7–728.7	0.184–0.203	0.047–0.050
15.0	881.0	881.0×10^5	12777.8	150.0	522.4	1335.6	300.3	0.117	0.024
	825.1–971.7	825.1×10^5–971.7×10^5	11967.1–14093.3	122.2–177.5	485.9–562.9	943.2–1615.8	212.0–363.2	0.110–0.127	0.022–0.026
25.0	837.6	837.6×10^5	12148.4	164.9	470.9	425.2	95.6	0.050	0.009
	813.6–872.6	813.6×10^5–872.6×10^5	11800.3–12656.0	149.1–174.0	446.7–490.1	378.8–450.0	85.2–101.2	0.042–0.055	0.008–0.011

[a] Propellant transformation phase, starts at the time to reach 10% of the maximum gas pressure and ends with the falling gas pressure curve once the powder has been fully transformed.

parameters of these shooting traps compared with common blank cartridge hand-guns.

In our test set-up, the velocity of the gas jet was determined by simultaneous measurement of the firing pressure of the cartridge and the dynamic force at the target. As a shortcoming of this investigation it is only an approximation of the real velocity, as this model does not take into account the Laval-pressure [6]. After leaving the muzzle, the initially focussed gas jet changes into a turbulent stream. A turbulent stream is characterized by oscillations that are directed sideways to the longitudinal movement of the jet. Due to the turbulence, the gas jet is mixed with the surrounding fluid. Mass and the diameter of the gas jet increase downstream. As the total momentum of the jet remains constant, velocity decreases downstream [5,6]. The muzzle velocity of the gas jet of vole captive bolt devices (up to 2000 m/s) amounts to the measurements reported for blank-firing hand guns [6,15,20].

The calibre 9×17 central firing industrial cartridges are widely used in bolt guns, alarm weapons or slaughterers guns. Due to their intended use in power actuated machine tools to propel either a projectile or some other mechanical component part they differ from common blank cartridges in higher energy levels and a faster burnout of the propellant. Therefore, the peak pressure rises quickly and then tapers off (Fig. 5).

The location of the peak pressure and the shape of the pressure curve are determined by the burning characteristics (degressive, progressive, or neutral) of the powder used. Slower burning powders tend to have a flatter curve while faster powders a steeper curve. Many other factors like the crimping of the case, the pressure at which the burning takes place, the filling level of the blank cartridge and the spatial location of the powder within the cartridge in relation to the primer also influence the peak pressure and the shape of the pressure curve [7,23]. Rothschild and Tschan found that the powder mass of blank cartridges varies up to $\pm 3\%$ within one ammunition lot [24]. There is also a major difference between the pressure curve of blank cartridges and projectile ammunition. If the cartridge contains a projectile, the powder gases spread into a defined volume which increases with increasing velocity of the bullet. In contrast, gas pressure of a blank cartridge does not encounter noticeable resistance after bursting the crimping of the case and the shock wave streams at high velocity into the barrel [6]. Therefore, for blank cartridges, especially in vole captive bolt devices with a very short tube between cartridge mouth and muzzle, the whole process of combustion shows a wide range. As a limitation of the study, the effect of the pressure spread on the obtained velocities and the dynamic force could not be determined due to the limited significance of three shots per distance.

Vole captive bolt devices deserve special attention in the field of forensic traumatology. German weapons and firing legislation, which are based on the C.I.P. (Commission Internationale Permanente pour l'épreuve des armes à feu portatives), categorize these gadgets as stationary shooting apparatus that are not intended for handheld use. The C.I.P. is a State International Organisation composed of thirteen countries that has been set up to check the activities of the national proof houses and, in particular, to guarantee the presence in each country of laws and regulations to assure the efficient and uniform testing of firearms and ammunition. According to C.I.P. regulations, the maximum gas pressure of industrial blank cartridges is limited to 1450 bar (1450×10^5 Pa, 21,030 psi) [25]. Under ballistic considerations, the relevant parts of all vole captive bolt devices that bear an official proof-test mark are identical. Therefore, the findings of the present investigation can be applied to other vole captive bolt devices [1].

The principle of self-triggering weapons as a pest control mean to get rid of detrimental rodents is known in other cultural areas too. Literature contains three reports on deaths due to illegally

manufactured mole guns [26–28]. In contrast to the vole captive bolt devices, these mole guns are loaded with ammunition containing pellets or a projectile and are completely legally unfounded.

5. Conclusion

The present investigation of the ballistic background of powder actuated vole captive bolt devices demonstrates that the unique design features (only a short tube between cartridge mouth and muzzle and narrow diameter of the muzzle which is necked down from 9 to 4 mm) of these gadgets are responsible for the high firing pressure, velocity and force of the gas jet resulting in a high energy density of the jet. These findings explain the trauma mechanics of the extensive tissue damage observed in our previous investigation.

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